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Research on the Effects of Biochar Addition on Soil Carbon Emissions: CO_2 and CH_4

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ABSTRACT

Soil carbon emissions significantly influence the global carbon balance as a major component of the terrestrial carbon pool. Biochar, an emerging soil amendment, has garnered significant interest for its potential to enhance carbon sequestration, improve soil fertility, and mitigate greenhouse gas emissions. However, the impacts of biochar on soil CO2 and CH4 emissions are complex and context-dependent, varying with biochar properties, soil types, and environmental conditions. Integrating proposed mechanisms for biochar-induced soil greenhouse gas mitigation with statistical analyses of published literature, this review systematically examines the effects of biochar on CO2 and CH4 emissions and identifies future research priorities. Specific focus is given to biochar produced at pyrolysis temperatures of 500-600 °C, its application in flooded soils, and its effects within straw-return agricultural systems. Through critical analysis of existing literature, this review aims to offer insights to guide further research and practical applications in this field.

KEYWORDS

Environmental soil; Carbon emissions; Biochar.

1. INTRODUCTION

With the escalating severity of global climate change, soil has garnered significant attention as one of the largest terrestrial carbon pools, primarily due to its carbon cycling processes, which exert a substantial influence on the global climate [1,2]. Greenhouse gases, particularly carbon dioxide (CO_2) and methane (CH_4) released from soils, constitute a major portion of global emissions and play a significant role in global warming [2]. CO_2, a principal greenhouse gas, directly affects Earth's energy balance and climate system through atmospheric concentration changes. Soil respiration, a critical component of the soil carbon cycle, is a major source of atmospheric CO_2, driven by the decomposition of soil organic carbon and microbial activity [3,4]. Methane, possessing a global warming potential approximately 28 times greater than CO_2 over a 100-year timescale, is significantly emitted from ecosystems like paddy soils and wetlands. Under waterlogged conditions, anaerobic environments promote methanogen metabolism, enhancing CH_4 release, a process particularly pronounced in deep anoxic soils (100-120 cm) [5]. Globally, annual CH_4 emissions from paddy soils alone exceed 3.1×10^{11} kg, contributing approximately 15% of total agricultural greenhouse gas emissions. As a nation with extensive arable land and the highest agricultural greenhouse gas emissions, China's annual agricultural emissions account for about 17% of the global total [6].

Consequently, mitigating soil-derived CO_2 and CH_4 emissions is crucial for advancing low-carbon agriculture and addressing climate change.

Biochar, a stable, carbon-rich material produced by pyrolyzing biomass under oxygen-limited conditions, has received extensive attention in recent years for soil improvement and environmental protection. Often termed "biomass-derived black carbon," it exhibits significant potential as a long-term carbon sink [7]. Produced from diverse feedstocks—including organic/industrial wastes (e.g., sludge, manure), plant residues (e.g., leaves, shells, seeds, corn cobs), and wood products (e.g., sawdust, wood chips, bark)—under defined pyrolysis conditions (temperature, duration), biochar possesses a wide range of physical and chemical properties depending on the feedstock and pyrolysis parameters [8]. Numerous studies report that biochar application improves soil properties and enhances carbon sequestration. Biochar influences soil CO_2 and CH_4 release by modifying soil physicochemical properties and biology. For instance, it can increase soil pH, cation exchange capacity (CEC), organic carbon (OC) content, electrical conductivity (EC), and nutrient availability [9]. Biochar amendments also improve soil physical properties, such as reducing bulk density and enhancing soil structure, while increasing water-holding capacity. These changes create an environment with improved aeration, moisture, and nutrient status, subsequently altering the composition, abundance, and activity of soil microbial communities [10]. This, in turn, affects the activity of functional microorganisms involved in carbon emissions, influencing organic carbon decomposition and the release of CO_2 or CH_4. For example, the porous structure of biochar (porosity: 40-70%) can enhance soil aeration, significantly reducing CH_4 emissions under waterlogged conditions (e.g., in paddies). Ali et al. [11] found that combined biochar and silicate amendments markedly suppressed seasonal CH_4 emissions. Conversely, in arid and semi-arid soils, biochar's enhanced water retention capacity (30-50% higher than control) may sustain microbial activity, promoting CO_2 release. Sun et al. [12] observed on the Loess Plateau that biochar-treated soil maintained a CO_2 emission rate of 0.8 μmol m^{-2} s^{-1} during dry periods, 45% higher than the control.

Despite biochar's potential to improve numerous soil properties, research outcomes regarding its impact on greenhouse gas emissions are inconsistent [13]. Low-temperature biochar (~300°C), retaining more labile organic matter, can stimulate soil organic carbon (SOC) decomposition via a "priming effect," increasing short-term CO_2 emissions. In contrast, high-temperature biochar (>600°C), characterized by a stable carbonized structure, often reduces carbon mineralization rates, enabling long-term carbon sequestration [14]. Furthermore, biochar's influence on microbial diversity and composition is variable. Its promotion of methane-oxidizing bacteria (e.g., Methylocystis) is more pronounced in acidic soils, while in alkaline conditions, it may enhance the competitive advantage of methanogens (e.g., Methanobrevibacter), potentially increasing CH_4 emissions [15]. The drivers of these inconsistent responses are diverse, including heterogeneity in soil type, biochar application rate, the relationship between biochar properties (determined by feedstock and pyrolysis conditions), and experimental design (laboratory, greenhouse, field). Therefore, this review aims to systematically synthesize the mechanistic framework governing biochar's impact on soil CO_2 and CH_4 emissions by integrating data from laboratory incubations, field experiments, and model simulations. Adopting a soil-biochar-microbe interaction perspective, we propose optimized application strategies, providing cutting-edge insights and a theoretical foundation for future research and practice.

2. EFFECTS OF BIOCHAR AND ENVIRONMENTAL FACTORS ON SOIL CO_2 EMISSIONS

Pyrolysis temperature and feedstock composition are core determinants of biochar's carbon stability and microbial effects. Low-temperature biochars (300-400°C) retain higher proportions of labile organic matter (e.g., sugars, proteins) and polar functional groups, potentially stimulating soil organic carbon (SOC) mineralization via the "priming effect". For instance, Choudhary et al. [16] reported

16% higher cumulative CO_2 emissions from soils amended with 1% farmyard manure biochar (400°C) compared to high-temperature rice husk biochar (600°C), directly correlating with its elevated water-soluble organic carbon (WSOC) content (125 mg g^{-1}). Conversely, high-temperature biochars (≥600°C) exhibit advanced aromatization (H/C < 0.5), reducing soluble carbon release and short-term CO_2 emissions. This temperature-dependent effect persists long-term; Lehmann et al. [17] observed an 82% carbon retention rate for high-temperature biochar (700°C) in tropical soils after 10 years, significantly exceeding the low-temperature counterpart (54%). Furthermore, microbial decomposition optimally proceeds at a soil organic matter C/N ratio near 25:1. Ratios <25:1 accelerate decomposition, while ratios >25:1 limit microbial activity due to nitrogen scarcity, slowing organic matter mineralization and potentially inducing crop N competition. Given biochar's inherently high C/N ratio (typically >25:1), its application perturbs soil C/N stoichiometry, thereby influencing carbon sequestration dynamics. Consequently, biochar's C/N ratio (20-200) directly regulates microbial metabolic pathways, as substantiated by Liu et al [18], who identified soil C/N stoichiometry as a critical factor governing biochar stability and SOC transformation.

Biochar effects exhibit pronounced soil-type dependency. In alkaline soils, biochar typically enhances microbial activity by modestly reducing pH (e.g., 7.83 to 7.78) and increasing dissolved organic carbon (DOC). However, high application rates (e.g., 1%) can elevate carbon stability, thereby decreasing cumulative CO_2 emissions [16]. In acidic soils, biochar ameliorates soil acidity, improving nutrient availability and stimulating microbial respiration. Application rate significantly modulates biochar efficacy. Higher rates generally suppress soil CO_2 emissions more effectively. For example, increasing application rates from 1% to 5% significantly reduces cumulative CO_2 emissions. Biochar performance also varies with environmental conditions: its carbon-mitigation potential diminishes during freeze-thaw cycles but strengthens during warmer crop-growing seasons [12]. Additionally, below 0°C, the temperature sensitivity of soil respiration decreases 1.3- to 1.8-fold, indicating temperature-dependent variability in biochar's mitigation efficiency.

3. EFFECTS OF BIOCHAR PROPERTIES AND ENVIRONMENTAL FACTORS ON SOIL CH_4 EMISSIONS

Biochar properties significantly modulate soil CH_4 emissions. Feedstock type determines ash content and nutrient release potential: rice straw biochar (15-20% SiO_2) enhances aggregate stability, indirectly limiting CH_4 diffusion [19], whereas livestock manure-derived biochar (N > 20 g kg^{-1}) may stimulate methanogen metabolism. Zhou et al. [15] observed 43% higher CH_4 emissions in mangrove soils amended with high-N biochar, correlating with increased Methanobrevibacter abundance and enhanced sulfate-reducing bacterial activity. Biochar pH exerts buffering effects on soils. Alkaline biochar (pH 8-11) neutralizes acidic soils (e.g., red soil pH < 5.5) but alters micro-oxygen environments for CH_4 metabolism. Under acidic conditions, biochar promotes methane-oxidizing bacteria (e.g., Methylosinus), increasing CH_4 oxidation rates by 25-50%. Conversely, in neutral-to-alkaline soils, elevated pH inhibits methane oxidation while providing favorable bicarbonate substrates for methanogens, thereby increasing emissions. Ouyang et al. [20] demonstrated 38% higher CH_4 emission rates in alkaline soil (pH 7.8) post-biochar amendment in Haizhu Wetland (Guangzhou), linked to reduced soil redox potential (Eh: +200 to -50 mV) and a shift toward hydrogenotrophic methanogenesis dominance.

Biochar impacts on CH_4 emissions exhibit time-dependent patterns. Short-term (<3 months) amendments often stimulate anaerobic SOC decomposition, increasing CH_4 production. Li et al. [18] demonstrated that biochar shortened methanogenesis lag phases by 6.5-11.7% and increased maximum methanogenic rates (R_{max}) by 24.97 ± 0.23% through enhanced electron transfer efficiency. Similarly, Qi et al. [27] reported elevated methane yields (725 mL g^{-1} VS d^{-1}) in reactors amended with 900°C biochar, achieving 75% theoretical CH_4 content versus 60% in controls, attributable to improved bioavailability of Fe, Co, and Ni trace elements. Metagenomic analyses confirmed concomitant increases in methanogenic enzyme gene abundance and activity. Conversely, long-term (>1 year) studies consistently show CH_4 suppression. Biochar improves soil structure, enhances aeration, and modulates pH, creating favorable habitats for methane-oxidizing bacteria that inhibit methanogens. This inhibitory effect intensifies with application rate; high-dose amendments achieve sustained CH_4 reduction in prolonged cultivation. Singh et al. [22] documented 3% CH_4 and 18% N_2O emission reductions despite a 1.9% CO_2 increase, while Vijay et al. [23] corroborated biochar's efficacy in mitigating high-global-warming-potential (GWP) gases.

4. COMPREHENSIVE IMPACT

Biochar application plays a dual role in enhancing soil carbon sequestration and mitigating greenhouse gas emissions. Biochar itself is rich in stable carbon, contributing directly to long-term soil organic carbon (SOC) storage. Concurrently, it can suppress soil CO_2 and CH_4 emissions, thereby mitigating global warming. However, considerable uncertainty persists regarding biochar's impact on key SOC stabilization processes, hindering its large-scale implementation. Research suggests that soil-applied biochar may rapidly increase SOC levels due to its inherent recalcitrance. Furthermore, it might enhance the stability of native (non-biochar-derived) SOC, inhibiting its decomposition [24–26]. Alternatively, some studies propose that biochar reduces the loss of stable organic matter or specific labile carbon fractions . The influence of biochar on soil carbon dynamics is linked to its interactions with soil minerals. For instance, biochar may promote soil aggregate formation [27], enhancing the physical protection of SOC (including biochar-C) within aggregates . It can also form organo-mineral complexes [28, 29] or adsorb organic molecules like humic acids onto its surface [30], potentially affecting SOC stability.

Overall, the effects of biochar on soil carbon processes exhibit high variability. Consequently, the "carbon sequestration-emission reduction trade-off" associated with biochar application remains a core research controversy. Future efforts should prioritize interdisciplinary integration (e.g., soil science, ecology, environmental science) to elucidate biochar's mechanisms within soil ecosystems. Long-term field experiments and modeling studies are essential to clarify biochar's emission reduction efficacy and environmental benefits across diverse temporal scales and environmental conditions. Additionally, developing scientifically sound application guidelines is crucial to improve understanding and adoption by farmers and land managers, facilitating wider use in agriculture and environmental protection. Attention must also be paid to the energy consumption and environmental footprint of biochar production, necessitating the development of greener, more efficient production technologies to reduce costs and enhance overall sustainability. In summary, through rigorous research and strategic application, biochar technology holds significant potential to contribute to climate change mitigation, food security, and sustainable agricultural development.

5. CONCLUSION

Biochar demonstrates significant potential for influencing soil CO_2 and CH_4 emissions, although its effects are highly dependent on biochar properties and soil-environment interactions. Future research must transcend the limitations of studying single gases or short-term impacts. Developing optimized biochar application models from a systems ecology perspective is vital for supporting agricultural carbon neutrality goals. Comprehensive assessments considering biochar's effects on other soil properties (e.g., fertility, aggregate stability) and plant growth are essential to evaluate its full ecological and environmental benefits. Crucially, research must address the interactions between biochar, climate change, and other environmental factors (e.g., pollutant emissions) on soil greenhouse gas fluxes. Elucidating the specific mechanisms and impacts of biochar on soil CO_2 and CH_4 emissions under varying conditions will provide the scientific foundation necessary for its rational utilization in soil improvement and climate change adaptation strategies.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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